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MULTIVARIATE GEOMORPHIC ANALYSIS OF FOREST STREAMS: IMPLICATIONS FOR ASSESSMENT OF LAND USE IMPACTS ON CHANNEL CONDITION

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ABSTRACT

Multivariate statistical analyses of geomorphic variables from 23 forest stream reaches in southeast Alaska result in successful discrimination between pristine streams and those disturbed by land management, specifically timber harvesting and associated road building. Results of discriminant function analysis indicate that a three-variable model discriminates 10 disturbed from 13 undisturbed reaches with 90 per cent and 92 per cent correct classification respectively. These variables are the total number of pools per reach, the ratio of mean residual pool depth to mean bankfull depth, and the ratio of critical shear stress of the median surface grain size to bankfull shear stress. The last variable can be dropped without a decrease in rate of correct classification; however, the resulting two-variable model may be less robust. Analysis of the distribution of channel units, including pool types, can also be used to discriminate disturbed from undisturbed reaches and is particularly useful for assessment of aquatic habitat condition. However, channel unit classification and inventory can be subject to considerable error and observer bias. Abundance of pool-related large woody debris is highly correlated with pool frequency and is an important factor determining channel morphology. Results of this study yield a much needed, objective, geomorphic discrimination of pristine and disturbed channel conditions, providing a reference standard for channel assessment and restoration efforts.

KEY WORDS fluvial geomorphology; multivariate analysis; forest streams; aquatic habitat; channel units

INTRODUCTION

Driven largely by an interest in maintaining or restoring aquatic habitat, the evaluation of stream channel physical characteristics has become an important land management concern in western North America and elsewhere. In this regard, several techniques have been suggested for assessing specific aspects of channel condition using features of channel and catchment geomorphology. For example, sediment supply has been related to bed material textures (Dietrich *et al.*, 1989; Kinerson, 1990; Lisle and Madej, 1992) and to the volume of fine sediment stored in pools (Lisle and Hilton, 1992).

Interpretation of channel condition requires both a process-based understanding of fluvial geomorphology (Montgomery and Buffington, 1993; Whiting and Bradley, 1993) and a reference standard against which to judge the state of a channel. We assume that the pristine state of stream channels is the desired condition, particularly with respect to aquatic habitat (Reiser and Bjornn, 1979; Sullivan *et al.*, 1987). However, the geomorphology of forest streams is complex owing largely to the influence of flow obstructions such as large woody debris (LWD), resistant bank projections and large boulders (Zimmerman *et al.*, 1967; Swanson *et al.*, 1976; Keller and Swanson, 1979; Lisle, 1986a). Large variability between and within forest streams occurs

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particularly with respect to sediment supply and transport, channel geometry, and characteristics of structural features such as LWD (Klingeman and Emmett, 1982; Beschta, 1987; Lisle, 1989; Smith *et al.*, 1993a, b). This complexity makes quantification of forest channel morphology, processes and related effects of land use challenging. Few objective geomorphic criteria distinguishing pristine channels from those disturbed by land use have been developed in previous studies. A brief review is presented below.

Lisle (1986b) analysed the effects of LWD on hydraulic geometry (Leopold and Maddock, 1953), pool characteristics and storage of fine sediment in eight forest streams on Prince of Wales Island, southeast Alaska, along reaches that were either undisturbed or logged. LWD loading was considerably greater in the logged reaches. Consequently velocity was significantly less and depth and friction factor were significantly greater at a particular discharge in the disturbed streams. Logged streams had larger percentages of the bed surface covered by fine sediment, presumably owing to greater hydraulic roughness and more abundant low-energy environments caused by greater LWD loading (Lisle, 1986b; see also Buffington and Montgomery, 1992). There was no significant difference between reaches in forested and logged areas with respect to number of pools, distribution of residual pool depth (Bathurst, 1981), or width-to-discharge relations (Lisle, 1986b).

Hogan and Church (1989) employed hydraulic geometry to quantify hydraulic characteristics and predict availability of salmonid habitat in a logged and an undisturbed stream reach in the Queen Charlotte Islands, British Columbia, Canada. They found that flow in the disturbed channel tended to be wider, shallower and faster than predicted from hydraulic geometry–drainage area relations, and attributed this to land use impacts. These effects resulted in a smaller than predicted area of the channel being hydraulically usable for salmonids (Hogan and Church, 1989). Earlier work in two nearby pairs of basins indicated that logging increased channel width and riffle area and decreased pool area (Hogan, 1987).

Carlson *et al.* (1990) compared channel features in five relatively undisturbed stream segments in northeastern Oregon, U.S.A., with paired segments having one-quarter to one-half of their riparian forest removed. They found no significant difference between logged and undisturbed pairs with respect to number of pools per 100 m or percentage of stream area in pools.

Reeves *et al.* (1993) examined timber harvest effects on pool frequency, wood loading, and diversity of salmonid populations in 14 coastal Oregon channels. Difference in pool frequency between basins with low and high (> 25 per cent of basin harvested) timber harvest intensity was not consistently statistically significant; however, there appeared to be a decline in pool frequency with increasing harvest level. Both LWD loading and salmonid diversity were significantly less in basins with high harvest levels.

In a comparison study of 70 forest stream reaches in undisturbed, clear-felled and second-growth areas in southwestern Washington, U.S.A., Bilby and Ward (1991) found significant differences in the frequency of LWD-related pools. For a given channel width, undisturbed reaches had the greatest frequency while clear-felled reaches had the least. In the clear-felled areas, 90 per cent of the LWD-related pools were scour pools, while channels in the undisturbed areas had a much broader diversity of pool types. LWD loading was also significantly different between land uses, with undisturbed and second-growth areas having the highest and lowest loadings respectively (Bilby and Ward, 1991).

The present study quantifies geomorphic characteristics of 23 gravel-bedded, forest stream reaches grouped into two categories: (1) undisturbed, and (2) heavily impacted by timber harvesting and associated road building (disturbed). Disturbed reaches are located within the area of immediate disturbance. We do not attempt to analyse the effects of varying disturbance levels, areas of disturbance, or distance from the disturbed site. We sample a limited range of slope, width and other characteristics in order to focus on the distinction between disturbed and undisturbed reaches within a narrow range of channel types. It is not our objective, however, to address channel-type classification in this study. All reaches have varying proportions of pool and bar topography, which is predominantly controlled by in-channel obstructions.

We develop an objective methodology for the assessment of channel condition based on measured geomorphic variables. Data are analysed using multivariate statistical techniques in order to produce discriminant functions for the classification of streams as either disturbed or undisturbed. Application of these discriminant functions to other sites may facilitate identification of those streams in need of restoration and those most at risk of being degraded from an undisturbed to a disturbed condition.

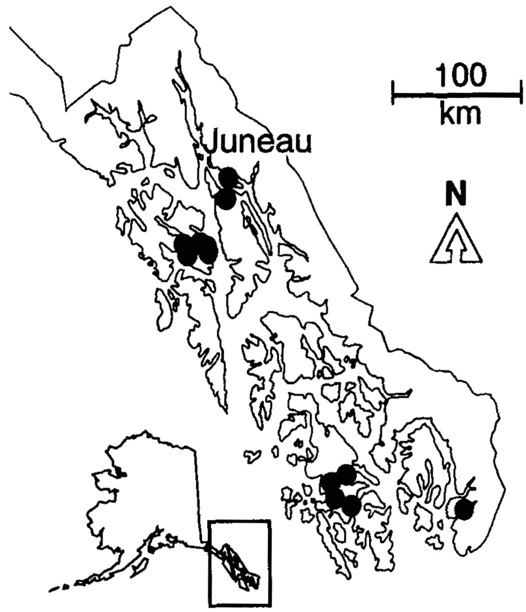

Figure 1. Study site locations in southeast Alaska, U.S.A.

STUDY AREA

We sampled streams over a wide geographic range in southeast Alaska (Figure 1). The area consists of the Alexander Archipelago and adjacent mainland. The extremely complex geology is composed of tectono-stratigraphic terranes accreted to and subducted below the continental margin from Cretaceous to Eocene time (Goldfarb *et al.*, 1988). Major assemblages from west to east include the Alexander–Wrangellia terrane, Gravina Belt, Taku terrane, and Coast Mountains (Gehrels *et al.*, 1990). Assemblage compositions include sedimentary, volcanic, intrusive and metamorphic rocks of Quaternary to Cambrian, and probable Proterozoic age (Gehrels and Berg, 1992).

Climate is maritime. Precipitation near sea level ranges from 66 to 561 cm a^{-1} (Selkregg, 1974). According to U.S. Geological Survey records and analyses for three long-term gauging stations, each in the vicinity of one of our three clusters of sampled reaches (Figure 1), there were no unusually large annual peak flows during the decade prior to this study. The largest flows occurred in Old Tom Creek near the southernmost cluster of reaches. At this gauging station, two flows having a recurrence interval between 5 and 10 years were recorded. There were four flows with a recurrence interval between 2 and 5 years and four flows with less than a 2 year recurrence interval (Jones and Fahl, 1994; U.S. Geological Survey, Anchorage, Alaska, preliminary annual peak flow frequency analyses).

Most soils in southeast Alaska are spodosols; however, entisols, inceptisols, cryofolists, cryosaprists and histosols are also present (Alexander *et al.*, 1989). Vegetation below the alpine zone is predominantly Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) forest.

Most sampled reaches are active spawning and rearing sites for a variety of anadromous and resident fish, including coho (*Oncorhynchus kisutch*), chum (*O. keta*), and pink (*O. gorbuscha*) salmon, cutthroat trout (*Salmo clarki*), and Dolly Varden (*Salvelinus malma*) char.

METHODS

In order to develop discriminant functions, we selected streams that were unambiguously either pristine or heavily disturbed by land use, thereby providing end members of the disturbance continuum. Disturbed

streams were commonly located in basins logged during the 1950s to 1970s, prior to the implementation of more recent protective management practices. The riparian forests were cut to the stream banks and much of the in-channel LWD was removed. In some cases, heavy equipment may have been operated in the channel.

We selected channels within the range of gradient and bed grain-size distribution commonly associated with high-quality spawning and rearing habitat for salmonids and thereby most likely to be considered for habitat protection or restoration. Such streams are typically gravel-bedded with slopes less than 0·025. Study channels were unconfined and had sufficient floodplain development to establish a bankfull elevation. We only sampled streams that could be waded at low flow and had reasonable access.

Twenty-three stream reaches were sampled (Figure 1). A reach is defined by Hogan and Church (1989) as a length of stream channel with homogeneous morphological, sedimentological and hydrological features. Reach location within an identified stream segment was randomly selected by beginning sampling at a distance from the stream mouth or upper limit of tidal influence equal to a randomly selected multiple (1–10) of channel width. Each reach was approximately 20 channel widths long. Contiguous reaches in a single stream were sampled provided that gradient and other characteristics remained within selection criteria; however, each reach was analysed separately. At each site, channel slope was measured by a longitudinal bed survey along the channel centreline. Channel geometry and grain-size characteristics were measured by paired cross-sectional surveys and pebbles counts (Wolman, 1954) at intervals of approximately five channel widths.

While bankfull elevation could generally be estimated with confidence, measurement of bankfull width was subject to error, owing to local effects of in-channel obstructions, bank erosion and non-alluvial banks. For this reason the active channel width (W_{ac}) and elevation of the active channel margin were used as reference points and scaling factors for some dimensions of interest. We defined the active channel as that portion of the channel in which flows occurred frequently enough to keep vegetation from becoming established. We observed such flows in some reaches during moderately intense rainfall events, which were equalled or exceeded several times each year. Active channel margins were readily distinguishable by a sharp change from unvegetated to vegetated banks at an elevation markedly less than bankfull flow. In the case of vertical banks, active channel width, bed width, and bankfull width were all equal. For each cross-section, bankfull depth was calculated as the bankfull cross-sectional area within W_{ac} divided by W_{ac}.

At all sites, channel units and related obstructions were inventoried and characterized in detail. Channel units consist of various types of pools and shallows that are the basic morphological components of a reach (Hogan and Church, 1989) and are important descriptors of aquatic habitat (Bisson *et al.*, 1982; Sullivan, 1986). We developed objective, non-discharge-dependent criteria for channel unit classification modified from Bisson *et al.* (1982) and Sullivan (1986). We included all units wider in the cross-stream direction than 0·1 W_{ac}. The wetted channel area was subdivided into pools and shallows on the basis of bed elevation relative to active channel margin elevation (Table I). The reach was further partitioned into units including riffles, glides, various types of pools, and cascades based on bed gradient, morphology and hydraulic characteristics (Table I).

For a unit to be classified as a pool, the elevation difference between the deepest point of the unit and the active channel margin had to be at least 5 per cent of the active channel width. Although this 5 per cent criterion was generally successful, it was not appropriate for all channel widths. It successfully classified units we qualitatively described as pools at all sites except Bambi Creek. This reach was unique in the dataset owing to its narrow (4 m) active channel width. In this case, pools were identified visually, based on similarity to objectively defined pools at our other sites.

Identification of plunge pools and underscour pools was based on the hydraulic conditions apparently responsible for their formation. In some cases this scouring turbulence or flow constriction was not active at the time of the survey, requiring a judgment to be made regarding the likely hydraulic conditions at higher flow.

Pool margins could commonly be identified by breaks in bed topography, therefore in most cases pool area could be confidently measured despite variations in stage. However, an increase in discharge might flood large areas of the bed having planar topography, thereby rapidly increasing the area in glides, riffles or cascades. This source of error affects the usefulness of comparisons between channels based on proportional

Table I. Channel unit definitions modified from Bisson *et al.* (1982) and Sullivan (1986)

Pool	Closed topographic depression in which the elevation difference between the lowest point of the unit and the active channel margin is at least 0·05 W_{ac} (only appropriate for a limited range in W_{ac})
Non-obstruction-related	Pools, unrelated to any non-alluvial (including LWD) obstruction, that are formed by interactive adjustments of fluid forces, sediment transport, and bed and bank topography in alluvial channels (Dietrich and Whiting, 1989: Nelson and Smith, 1989a, b); includes pools formed by tributary confluence
Obstruction-related	Pools scoured by a local increase in lift and drag forces caused by flow deflection, constriction, or increased local turbulence induced by a non-alluvial (including LWD) obstruction (Lisle, 1986a; Smith, 1990). We consider channel banks to be obstructions if they sharply deflect flow and resist deformation to the extent of preventing meander development (see discussion in Lisle, 1986a)
Plunge	Scour is by flow plunging over an obstruction
Underscour	Scour is by flow constricted under an obstruction
Lateralscour	Long, narrow pool scoured along the channel margin, caused by flow impinging on a resistant, non-alluvial bank
Eddy	Lies downstream of an obstruction. Eddying flow separates from the main flow at the obstruction edge and commonly continues to the channel margin
Scour	Obstruction-related, but not belonging to one of the above categories
Shallow	Water depth less than in a pool
Glide	Bed slope is less than 0·02
Riffle	Bed slope is between 0·02 and 0·04 inclusive
Cascade	Bed slope greater than 0·04
Slipface	Flow is over the slipface of a bar
Step-pool	Flow is over a sequence of cobble, boulder or woody debris clusters separated by pooled water

area of various units, therefore we used such comparisons only in a limited way. Unit frequency provided a more objective measure; however, these comparisons should also be made with caution owing to potential observer bias regarding the subdivision of adjoining pools and the assessment of hydraulic conditions at high discharge.

Pool-related obstructions were inventoried and categorized. These included various types of LWD pieces and accumulations, boulders, resistant banks, bank projections and in-channel bank remnants. We measured dimensions of these in-channel obstructions and their orientation relative to the flow. Characteristics of obstructions and their effect on channel unit dimensions and distribution are subjects of a forthcoming publication.

Based on our observations and on results of previous studies discussed above, the following 11 variables were judged to have good potential for objectively discriminating between disturbed and undisturbed streams:

W_{ac}/h_{bf} = ratio of the reach-averaged active channel width to reach-averaged bankfull depth

τ_{c50}/τ_{bf} = ratio of the critical shear stress for the reach-averaged median surface grain size (D_{50}) to the reach-averaged bankfull shear stress

where $\tau_{c50} = 0{\cdot}05(\gamma_s - \gamma)(D_{50})$ (Vanoni, 1975); γ = specific weight of water; γ_s = specific weight of the sediment; $\tau_{bf} = \gamma h_{bf} S$, the reach-averaged bankfull basal shear stress; S = reach-averaged bed slope

A_p/A_{rh} = ratio of the reach-averaged pool area to wetted channel area of the reach

h_r/h_{bf} = ratio of the reach-averaged residual pool depth to reach-averaged bankfull depth

LWD/rh = number of pool-associated LWD pieces per reach

$pools/rh$ = number of pools per reach

$plunge\ pools/rh$ = number of plunge pools per reach

$underscour\ pools/rh$ = number of underscour pools per reach

$lateralscour\ pools/rh$ = number of lateralscour pools per reach

$eddy\ pools/rh$ = number of eddy pools per reach

$scour\ pools/rh$ = number of scour pools per reach

The ratio τ_{c50}/τ_{bf} is a measure of the shear stress theoretically required to mobilize the observed D_{50} scaled by the total boundary shear stress at bankfull discharge. This ratio may be interpreted as a measure of textural response to both sediment supply and hydraulic roughness elements (e.g. in-channel obstructions) in a bankfull threshold channel framework (Buffington and Montgomery, 1992). It may alternatively be interpreted as a measure of bed surface mobility where a fixed discharge transport threshold is not assumed. We employ a dimensionless critical shear stress value of 0·05 to define τ_{c50}; however, a wide range of values has been reported for this constant (see discussions by Miller *et al.* (1977) and Petit (1994)).

Using the above candidate variables, discriminant function analysis (Dunteman, 1984) was employed to quantitatively distinguish between disturbed and undisturbed reaches and to develop a preliminary classification model to apply to other gravel-bedded forest streams. The analyses included two separate procedures; (1) stepwise discriminant analysis, and (2) canonical discriminant analysis. A backward stepwise elimination procedure was used to determine the subset of original variables that best discriminated between groups. Variables were chosen that minimized the ratio of within-group (disturbed or undisturbed) sum of squares to total sum of squares for the model (SAS, 1987). The selection procedure stopped when means of all remaining variables were significantly different for the two groups at the 0·01 probability level (SAS, 1987). Scatter plots of each preferred variable against channel slope were examined to verify group discrimination.

Canonical discriminant analysis (Dunteman, 1984; Norusis, 1985; SAS 1987) was applied to the preferred variables in order to develop a linear combination (canonical variable) that summarized between-class variation, thereby allowing disturbed and undisturbed streams to be successfully discriminated (SAS, 1987). A canonical variable ($CANx$) derived from (for example) three predictor variables can be expressed as follows:

$$CANx = \beta_0 + \beta_1 X_1 + B_2 X_2 + \beta_3 X_3$$

where X values are the predictor variables and the β values are coefficients estimated from the data so that the ratio of between-group sum of squares to within-group sum of squares is maximized (Norusis, 1985). Each sampled reach was classified as disturbed or undisturbed on the basis of its posterior probability of membership, which is a function of $CANx$. The value of $CANx$ is not, however, a direct measure of group membership (Norusis, 1985; SAS, 1987). The rate of correct classification (agreement with field classification) and the degree of overlap in values of $CANx$ for disturbed and undisturbed reaches were used as measures of success of the discriminant function (Dunteman, 1984; Norusis, 1985).

RESULTS AND DISCUSSION

Study reach characteristics

The 10 disturbed and 13 undisturbed sampled reaches range in width from about 4 to 25 m and in gradient from 0·0017 to 0·0224. Drainage area varies from about 1 to 40 km^2, and D_{50} ranges from about 12 to 86 mm (Table II).

Channel unit distribution

Channel unit distribution differs markedly between disturbed and undisturbed reaches. In undisturbed channels, pools are the predominant type of channel unit. The mean proportion of wetted channel area consisting of pools is 55 per cent compared to 34 per cent for disturbed channels (Figure 2). In disturbed streams,

Table II. Site characteristics. Dimensional units are expressed in metres unless otherwise noted

Reach	DA (km^2)	Use	L	S	W_{ac}	h_{bf}	W_{ac}/h_{bf}	D_{50}
12-mile	29·63	D	360	0·0021	19·5	1·07	18·2	0·0241
Bambi	1·12	D	80	0·0091	4·0	0·33	12·2	0·0174
Cable	22·58	D	300	0·0017	14·9	0·96	15·6	0·0131
Fubar 1	9·76	D	360	0·0106	16·0	0·73	21·8	0·0368
Fubar 2	8·98	D	300	0·0127	15·1	0·84	18·0	0·0568
Maybeso 1	39·51	D	400	0·0071	20·2	1·22	16·6	0·0494
Maybeso 2	39·35	D	500	0·0065	24·6	0·93	26·3	0·0361
Maybeso 3	36·81	D	324	0·0023	23·7	1·00	23·8	0·0362
Maybeso 4	35·91	D	436	0·0036	22·1	1·13	19·4	0·0462
Muri	8·32	D	300	0·0149	13·1	0·63	20·8	0·0441
E Fk. Trap	5·77	U	172	0·0125	7·8	0·70	11·2	0·0242
Fish	18·53	U	280	0·0224	11·9	0·59	20·1	0·0456
Fowler 1	20·93	U	225	0·0062	15·6	0·77	20·4	0·0139
Fowler 2	15·60	U	210	0·0055	8·6	0·82	10·5	0·0189
Hook	21·37	U	250	0·0109	13·5	0·87	15·4	0·0272
Trap 1	10·20	U	220	0·0055	11·3	0·91	12·4	0·0167
Trap 2	10·06	U	230	0·0071	12·1	0·71	17·0	0·0158
Trap 3	9·92	U	172	0·0093	9·0	0·67	13·5	0·0137
Trap 4	8·91	U	148	0·0088	7·8	0·75	10·4	0·0116
Trap 5	8·72	U	230	0·0110	11·5	0·71	16·3	0·0159
Trap 6	8·27	U	200	0·0120	12·7	0·70	18·0	0·0134
Weasel 1	7·70	U	161	0·0138	8·8	1·08	8·1	0·0863
Weasel 2	7.15	U	242	0·0023	13·6	1·00	13·6	0·0254

DA is drainage area. D indicates disturbed and U undisturbed. L is reach length; S is slope of the bed centreline; W_{ac} is active channel width; h_{bf} is bankfull depth; D_{50} is median grain size of the bed surface

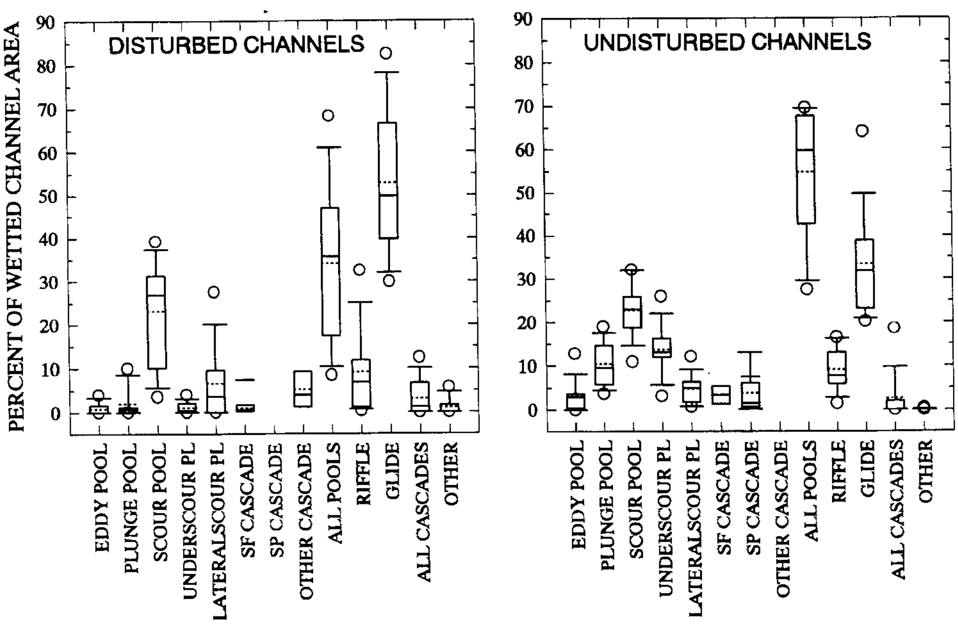

Figure 2. Box plot representation of the distribution of channel units in disturbed and undisturbed reaches. Boxes indicate the 25th and 75th percentiles; solid lines denote the 50th percentile; dotted lines indicate the mean; capped bars represent the 10th and 90th percentiles; circles indicate the 5th and 95th percentiles. See Table I for channel unit definitions

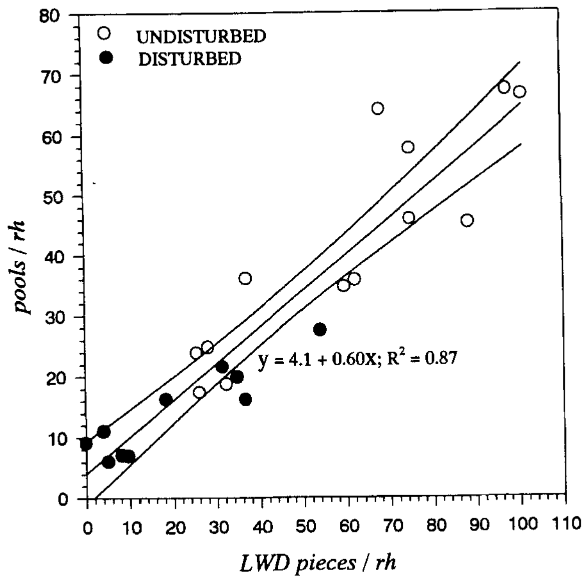

Figure 3. Number of pools per reach as a function of number of pool-associated LWD pieces per reach. The regression line is shown with 95 per cent confidence interval estimates

glides are the dominant unit, making up 53 per cent of the wetted channel area, compared to 33 per cent in undisturbed reaches. In both land use types, scour pools are the most common type of pool. Riffles are approximately equally widespread in both land use types, although they make up as much as 32 per cent of one disturbed reach (Figure 2).

We attribute differences in channel unit distribution between disturbed and undisturbed reaches primarily to differences in pool-associated LWD loading, which is generally greater in the undisturbed reaches. Pool frequency is clearly related to LWD loading (Figure 3). On average, there are 60 pool-related LWD obstructions per reach in undisturbed channels, compared to 20 in disturbed streams (Figure 3). Land-management-related loss of LWD may be caused by removal during logging, post-logging stream cleaning, reduced riparian recruitment, or destabilization of LWD pieces owing to altered discharge regimes. Of the pools we inventoried, 96 per cent are obstruction-related, including pools scoured by flow impinging on a resistant bank. Scour around LWD obstructions accounts for 80 per cent of the pools in undisturbed streams, in contrast to 55 per cent in disturbed streams. Although our LWD inventory includes only pool-associated LWD, pool frequency in forest streams has also been shown to be positively correlated with total LWD loading (Montgomery *et al.*, 1995).

Robison and Beschta (1990) presented an analysis of five undisturbed streams in southeast Alaska including the portions of Bambi and Trap Creeks examined in this study. They found that, on average, 57 per cent of the undisturbed channel length consisted of pools, in excellent agreement with results of this study. However, they found that 17 per cent of undisturbed channels consisted of glides and 26 per cent of riffles (Robison and Beschta, 1990). In contrast, the mean values for undisturbed streams in the present study are 33 per cent and 9 per cent respectively. This discrepancy reflects differences in methodology that limit direct combination of datasets and illustrates the need for objective, non-discharge-dependent criteria, such as presented in this study, for channel unit identification and measurement.

Pool types as discriminators

Scatter plots of the frequency of each of five pool types against slope illustrate that, in general, disturbed reaches plot separately from undisturbed reaches, thereby implying an effect of land use (Figure 4). Based on

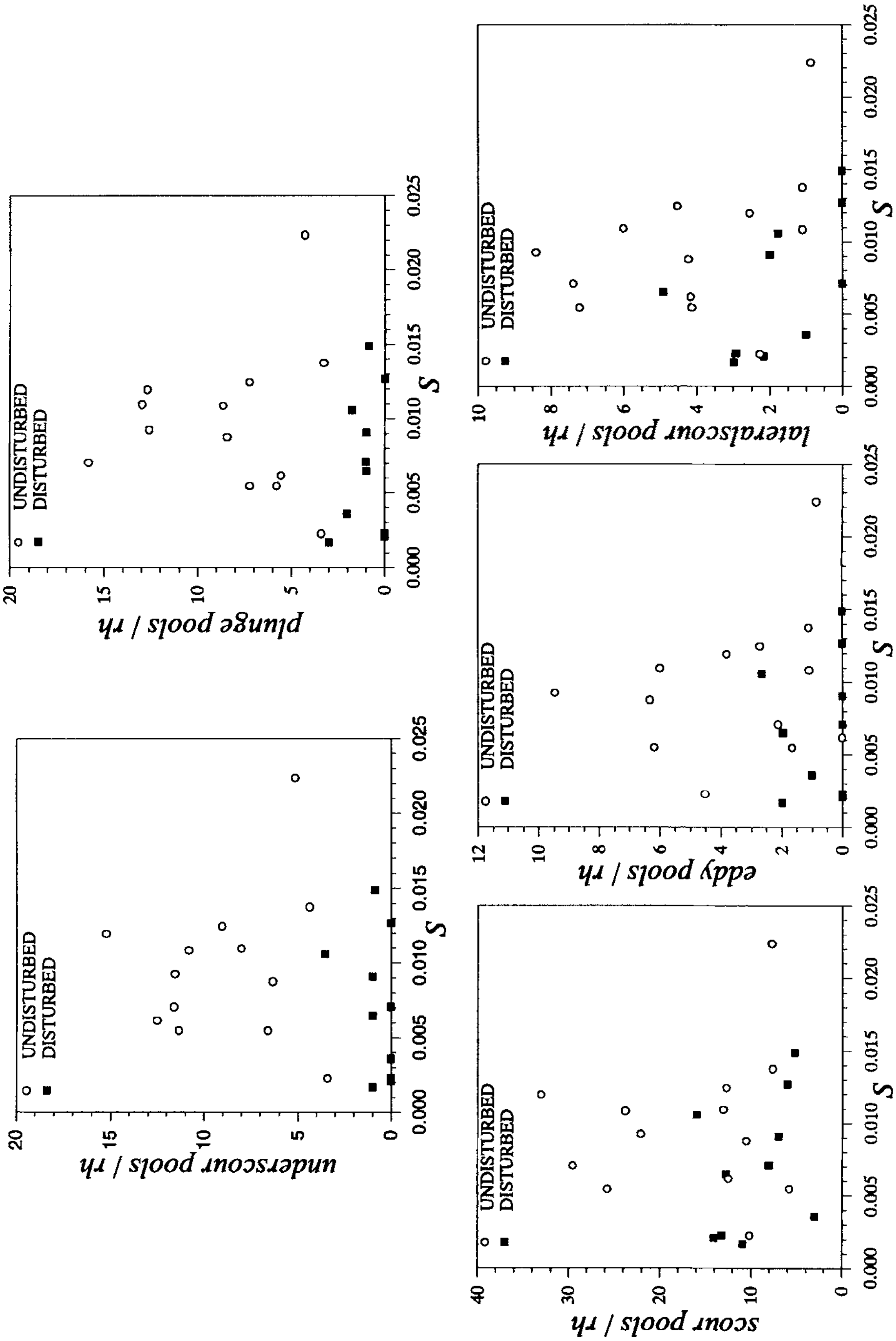

Figure 4. Frequency of pool types plotted against channel slope for the two land use categories examined

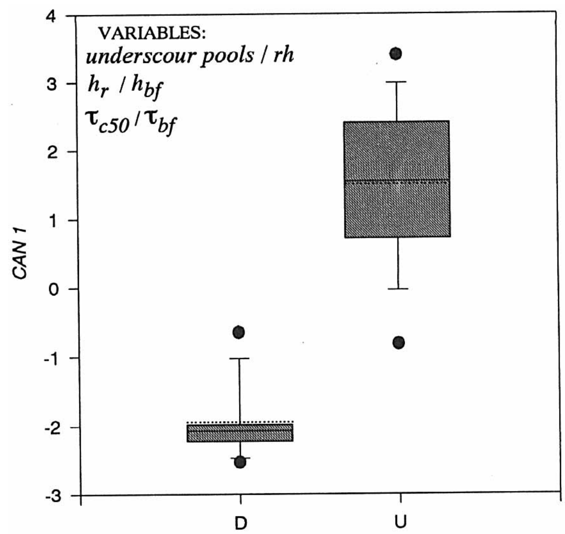

Figure 5. Box plot representation of the distribution of *CAN1*, a linear combination of the variables *underscour pools/rh*, h_r/h_{bf} and τ_{c50}/τ_{bf} for disturbed (D) and undisturbed (U) reaches. See caption to Figure 2 for explanation of box plot symbols

inspection of scatter plots and stepwise variable selection, the most successful of these variables as discriminators are *underscour pools/rh* and *plunge pools/rh* (Figure 4).

Canonical discriminant analysis using either of these two pool types in combination with h_r/h_{bf} and τ_{c50}/τ_{bf} (other good discriminators as discussed below) results in highly successful classifications of the study reaches (Figures 5, 6). Using *underscour pools/rh*, all reaches are correctly classified. Using *plunge pools/rh*, the disturbed reach, Maybeso 1, is misclassified as undisturbed.

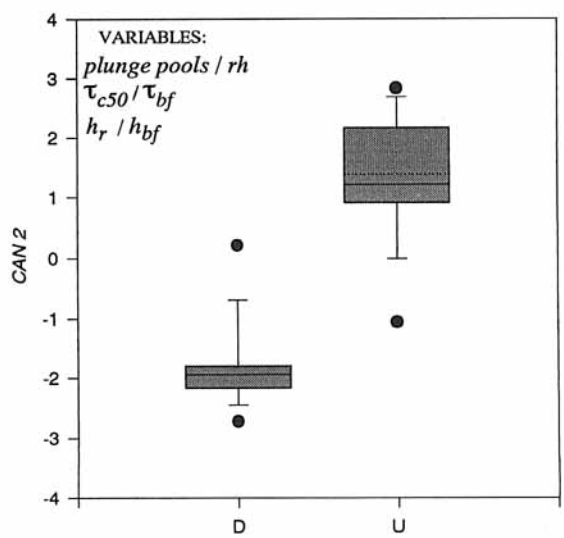

Figure 6. Box plot representation of the distribution of *CAN2*, a linear combination of the variables *plunge pools/rh*, h_r/h_{bf} and τ_{c50}/τ_{bf} for disturbed (D) and undisturbed (U) reaches. See caption to Figure 2 for explanation of box plot symbols

Pool type frequencies may be particularly useful discriminators for some applications because of the implications for availability and quality of aquatic habitat (Bisson *et al.*, 1982; Sullivan, 1986). However, pool type inventories are subject to error owing to differing inventory methodologies and observer bias, as discussed previously. Furthermore, all of the pool types are highly correlated with *pools/rh*. For these reasons, *pools/rh* is used in favour of individual pool type variables in the following analyses.

Variable selection

Examination of scatter plots of the candidate variables, listed previously, and stepwise variable selection analysis indicate that A_p/A_{rh} is not a good discriminator of land use condition, and it was consequently discarded from further analyses. We do not use *LWD/rh* owing to its high correlation with *pools/rh* (Figure 3). We tested for correlations among the remaining variables and between those variables and drainage area (*DA*) employing Pearson product moment correlation analysis using $P < 0{\cdot}05$ (SAS, 1987). W_{ac}/h_{bf} is strongly correlated with drainage area, as expected from considerations of hydraulic geometry (Leopold and Maddock, 1953). Although this variable shows promise as an indicator of land use effects (Lisle, 1981; Lyons and Beschta, 1983; Hogan and Church, 1989), our dataset is not large enough to isolate drainage area effects, therefore we do not use W_{ac}/h_{bf} in subsequent analyses.

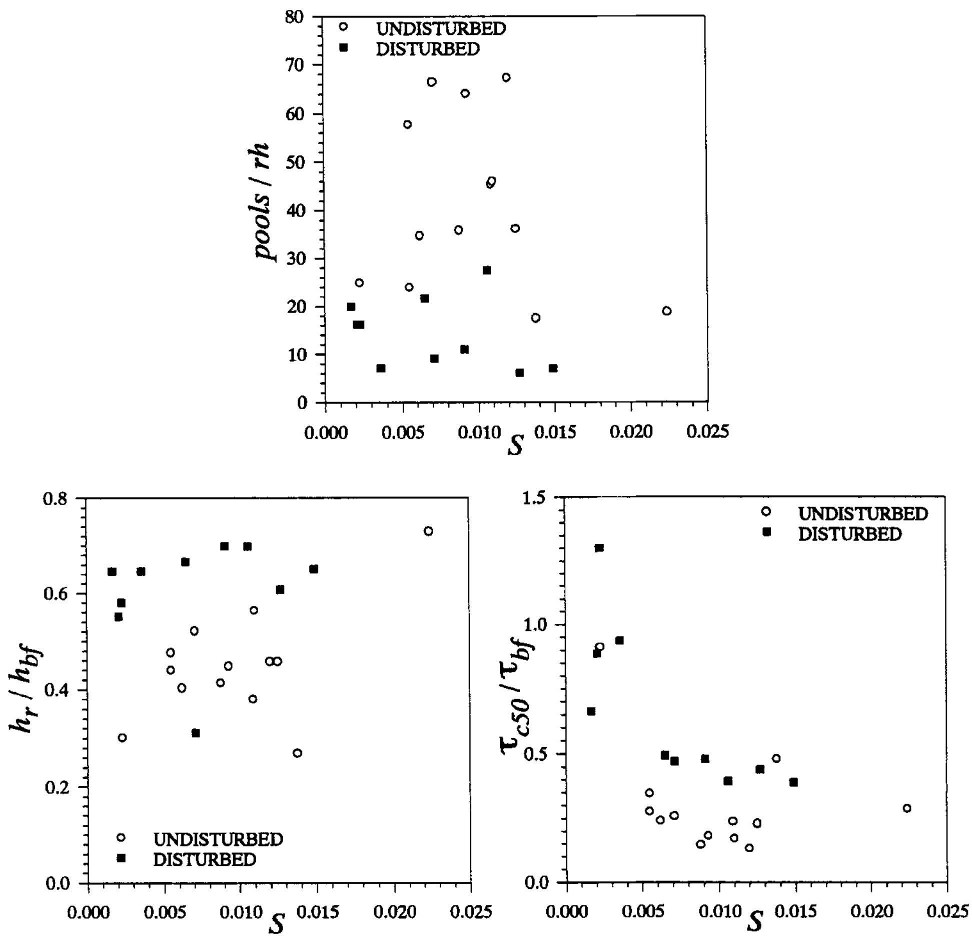

Figure 7. Distribution of the preferred variables for discrimination between disturbed and undisturbed reaches plotted against channel slope

The remaining variables, *pools/rh*, τ_{c50}/τ_{bf} and h_r/h_{bf}, produce good discrimination between land use types in both the stepwise procedure and scatter plot analysis (Figure 7) and are used in further analyses. For all reaches, there is a significant negative correlation between τ_{c50}/τ_{bf} and *pools/rh*. For the undisturbed reaches alone, this correlation is not significant, indicating that it is primarily an artifact of disturbance effects. That is, disturbed reaches tend to have larger values of τ_{c50}/τ_{bf} and smaller values of *pools/rh* than undisturbed reaches. The same reasoning applies to a significant positive correlation between τ_{c50}/τ_{bf} and *DA*. This correlation does not exist for the undisturbed sites alone, and for our dataset reaches with the largest drainage area are disturbed sites.

Three of the pristine reaches, Hook, Weasel 1 and Weasel 2, contain material delivered from recent upstream landslides. Such naturally occurring events are common in the region. Indeed, all of the reaches have probably been affected by mass wasting events in Holocene time. In the reaches recently affected by landslides, *pools/rh* tends to be midway between values for other pristine and disturbed streams. Therefore, inclusion of these reaches in the dataset has a conservative effect on distinctions between undisturbed and disturbed reaches.

We attribute the distinct pool frequency distributions (*pools/rh*) for the two land use conditions (Figure 7) to differences in pool-associated LWD loading. The disturbed reach with the largest value of *pools/rh* (Figure 7) is Fubar 1, which has the largest value of *LWD/rh* of any disturbed stream (Figure 3).

Disturbed reaches have relatively high values of h_r/h_{bf} (Figure 7). Several factors may contribute to this effect. LWD pieces remaining in these reaches tend to be larger logs, root masses and log accumulations that can form deep pools. Selective preservation of these large pieces results in high reach-averaged values of h_r. In addition, reduced LWD roughness may result in increased average flow velocity (Hogan and Church, 1989), which may increase residual depth of pools.

Large values of h_r/h_{bf} may also be caused by channel widening and a related decrease in h_{bf}. Channel widening can result from increased sediment supply following disturbance (Lisle, 1981; Lyons and Beschta, 1983; Hogan and Church, 1989), land-use-related alteration of the discharge regime (e.g. Harr, *et al.*, 1982; Hornbeck *et al.*, 1993), and increased effective shear stress following removal of the LWD component of flow resistance (Smith *et al.*, 1993a). Although the bed may respond to these changes by adjustments in bedload transport, slope, grain-size distribution or bar-pool topography (Dietrich and Whiting, 1989; Dietrich *et al.*, 1989), the banks are likely to respond by eroding. Bank erosion may also be caused

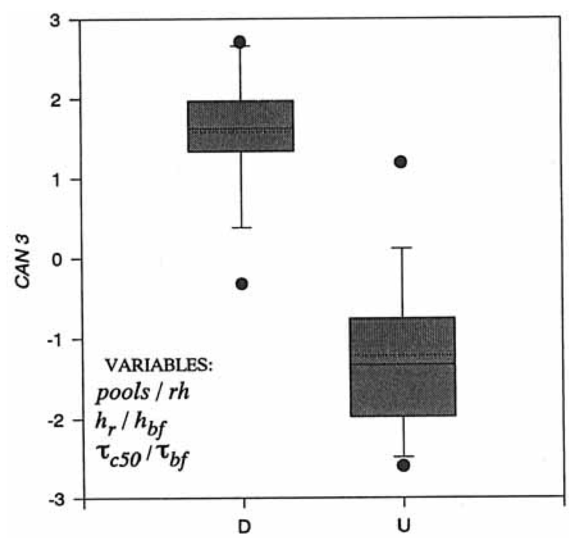

Figure 8. Box plot representation of the distribution of *CAN3*, a linear combination of the variables *pools/rh*, h_r/h_{bf} and τ_{c50}/τ_{bf} for disturbed (D) and undisturbed (U) reaches. See caption to Figure 2 for explanation of box plot symbols

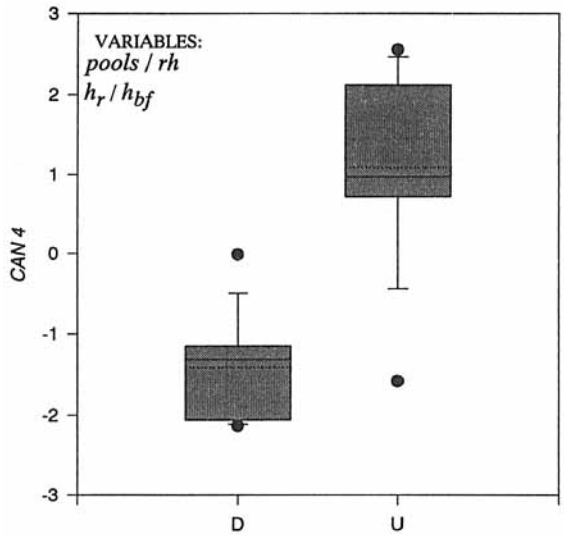

Figure 9. Box plot representation of the distribution of *CAN4*, a linear combination of the variables *pools/rh*, and h_r/h_{bf} for disturbed (D) and undisturbed (U) reaches. See caption to Figure 2 for explanation of box plot symbols

by loss of bank cohesion resulting from direct impacts during land use activities or loss of root strength following removal of the riparian forest.

Removal of LWD may affect h_{bf} by eliminating obstruction-related scour of the bed and banks. In other cases, local scour may be increased by exposing previously defended banks to flow (Smith *et al.*, 1993b). Disturbance-related reduction in h_{bf} coupled with the tendency for the residual depth of some obstruction-

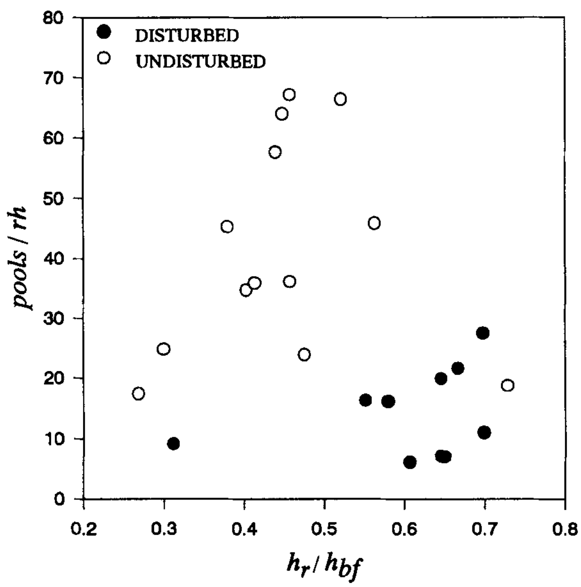

Figure 10. Distribution of disturbed and undisturbed reaches on a plot of h_r/h_{bf} versus *pools/rh*

Table III. Mean and standard deviation of preferred discriminant variables for the contiguous reaches in Maybeso and Trap Creeks. Values are expressed as a percentage of the same quantity for the other sampled reaches of like disturbance classification. For example, the mean value of the variable *underscour pools/rh* for the Maybeso Creek reaches is 23·0 per cent of that for the other sampled disturbed reaches

	Maybeso		Trap	
	mean	std dev.	mean	std dev.
underscour pools/rh	23·0	37·8	144·3	90·7
plunge pools/rh	90·9	72·6	36·0	160·5
pools/rh	92·3	80·8	195·7	124·1
h_r/h_{bf}	85·8	290·1	110·2	37·3
τ_{c50}/τ_{bf}	147·8	201·6	49·6	24·2

related pools to remain stable over a wide range in sediment flux (Smith, 1990) would tend to increase h_r/h_{bf}. The disturbed reach with the lowest value of h_r/h_{bf} (Figure 7) is Maybeso 1, which has the largest bankfull depth of the disturbed reaches (Table II).

Values of τ_{c50}/τ_{bf} are greater in disturbed than in pristine reaches (Figure 7). We believe that this reflects bed surface coarsening of disturbed channels following reduction of flow resistance formerly provided by LWD (Buffington and Montgomery, 1992). Weasel 2 has the largest value of τ_{c50}/τ_{bf} of the undisturbed reaches (Figure 7). This may be caused by input of coarse sediment from an upstream landslide, as discussed previously. Furthermore, this reach has relatively low LWD loading, possibly contributing to coarse surface grain sizes.

Canonical discriminant analysis using the three preferred variables (Figure 7) results in good discrimination by land use category (Figure 8). One undisturbed (Fish) and one disturbed (Maybeso 1) reach are misclassified in the analysis. Maybeso 1 has a value of h_r/h_{bf} characteristic of undisturbed reaches (Figure 7). Fish has the greatest slope of the undisturbed reaches (Table II) and plots close to the disturbed field in plots of each of the preferred variables (Figure 7). For the three-variable model:

$$CAN3 = -2{\cdot}73 - 0{\cdot}044\ (pools/rh) + 6{\cdot}08\ (h_r/h_{bf}) + 1{\cdot}94\ (\tau_{c50}/\tau_{bf})$$

An equally successful discrimination can be made using only *pools/rh* and h_r/h_{bf} (Figure 9). The reaches Fish and Maybeso 1 are misclassified using this model also. For this two-variable case:

$$CAN4 = 1{\cdot}24 + 0{\cdot}059\ (pools/rh) - 5{\cdot}75\ (h_r/h_{bf})$$

Both variables in this model can be measured objectively and relatively easily from cross-sectional surveys and elevation measurements of the bed and active channel margin, therefore this simple classification method may prove to be a particularly useful field tool when time and resources for channel analysis are limited.

An assessment of channel condition for a stream of interest can be made based on the canonical functions given above or, in the case of the two-variable model, by plotting values of *pools/rh* and h_r/h_{bf} (Figure 10). Although the two- and three-variable models are equally successful in discriminating land use category for the present dataset, we anticipate that with the addition of more data, the three-variable model will prove to be more robust.

Where aquatic habitat issues are of primary concern, isolating LWD-related pools as discriminant variables may be useful. Repeating the above discriminant analyses using the frequency of these pools, h_r/h_{bf} and τ_{c50}/τ_{bf} produces very similar results in that the same reaches (Fish and Maybeso 1) are misclassified. Using LWD-related pools and only h_r/h_{bf} improves this discrimination sufficiently that Maybeso 1 is correctly classified, leaving only Fish misclassified.

Our results are influenced by several contiguous reaches, particularly those in the disturbed Maybeso Creek and the undisturbed Trap Creek. The influence of the contiguous reaches depends upon the variable in question but is not extreme in any case (Table III). Therefore, we do not consider this influence to have a major effect on our conclusions. The greatest influence on the mean of any preferred discriminant variable occurs with *underscour pools/rh*. For the Maybeso Creek reaches, the mean value of this variable is 23 per cent of the value for the other disturbed reaches (Table III). Contrary to what might be expected, variability of the preferred discriminant variables between contiguous reaches is not consistently lower than between the other reaches of like disturbance classification (Table III). For example, variation of h_r/h_{bf} between the Maybeso Creek reaches is nearly three times as large as that between the other disturbed reaches (Table III).

SUMMARY

Important differences in channel unit distribution occur between disturbed and undisturbed stream reaches. A larger percentage of the wetted channel area is composed of pools in undisturbed streams, while disturbed channels contain a larger areal extent of glides (Figure 2). We attribute these differences to effects of pool-related LWD, which is generally more abundant in the undisturbed reaches and is positively correlated with pool frequency (Figure 3).

Discriminant function analysis applied to frequency of pool types indicates that the most successful discriminating variables are *underscour pools/rh* and *plunge pools/rh*. The importance of LWD is again illustrated here in that interaction of flow with LWD obstructions is the most common cause of plunge and underscour pools. Canonical discriminant analysis using either of these two pool types in combination with h_r/h_{bf} and τ_{c50}/τ_{bf} is highly successful in correctly classifying the study reaches. However, identification of pool types is subject to error and observer bias.

Using canonical discriminant analysis of objectively determined geomorphic variables, disturbed reaches can be successfully discriminated from undisturbed reaches by a linear combination of the following variables: *pools/rh*, h_r/h_{bf} and τ_{c50}/τ_{bf}. These three variables can be determined in an objective fashion independently of discharge. An equally successful discrimination can be made using only *pools/rh* and h_r/h_{bf}. These two variables are relatively easy to obtain, therefore this simplified classification model may prove to be a particularly useful field tool when time and resources for channel analysis are limited. However, additional data may indicate that the three-variable model is more robust owing to the inclusion of land use effects on surface grain size.

CONCLUSIONS

Within the range of gradient and width sampled, geomorphic characteristics presented herein quantify typical features of undisturbed, gravel-bedded forest streams in southeast Alaska, and perhaps old-growth forest streams in general. Documentation of the magnitude and variability of these geomorphic variables increases our general understanding of the structure and function of stream ecosystems in forested areas. Data from disturbed reaches illustrate how these characteristics can be affected by land use.

Results of this study demonstrate that pristine channel condition can be discriminated from that of management-disturbed channels by analysing objectively determined geomorphic variables using multivariate statistical techniques. Variation in preferred discriminant variables between land use categories is found to be greater than variation between reaches of like category in different catchments. Application of the presented canonical functions yields a much needed, objective, geomorphic discrimination of pristine and disturbed channel condition, providing a reference standard for channel assessment and restoration efforts. Such a standard may allow identification of streams most at risk of being degraded from a pristine to a disturbed condition and consequently in need of special land management consideration. Likewise, disturbed streams in need of restoration can be identified objectively, and restoration goals can be set to mimic geomorphic conditions, such as pool frequency, found in similar, undisturbed streams.

Our data are limited to forest, gravel-bedded channels in southeast Alaska. Clearly, additional research is needed to encompass a greater range of channel and catchment size and gradient and channel type, and

to refine models for channels in other environments. The order of preference of discriminant variables and value of model coefficients will likely change for other environments and land use practices. More research is also needed within reaches having similar catchment size and at varying distances from disturbance sites. Nevertheless, we believe the concepts and general procedures used herein to be broadly applicable, particularly in forest, gravel-bedded channels.

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REFERENCES

Alexander, E. B., Kissinger, E., Huecker, R. H. and Cullen, P. 1989. 'Soils of southeast Alaska as sinks for organic carbon fixed from atmospheric carbon-dioxide', in Alexander, E. B. (Ed.), *Proceedings of Watershed '89 a Conference on the Stewardship of Soil, Air, and Water Resources*, R10-MB-77, USDA, Forest Service, Alaska Region, Juneau, AK, 203–210.

Bathurst, J. C. 1981. 'Discussion of bar resistance of gravel-bed streams', *Journal of the Hydraulics Division, American Society of Civil Engineers*, **104,** 1587–1603.

Beschta, R. L. 1987. 'Conceptual models of sediment transport in streams', in Thorne, C. R., Bathurst, J. C. and Hey, R. D. (Eds), *Sediment Transport in Gravel-Bed Rivers*, John Wiley & Sons, Chichester, 387–419.

Bilby, R. E. and Ward, J. W. 1991. 'Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington', *Canadian Journal of Fisheries and Aquatic Science*, **48,** 2499–2508.

Bisson, P. A., Nielsen, J. L., Palmason, R. A. and Grove, L. E. 1982. 'A system of naming habitat types in small streams with examples of habitat utilization by salmonids during low streamflow', in Armantrout, N.B. (Ed.), *Acquisition and Utilization of Aquatic Habitat Inventory Information*, Proceedings of a Symposium Held 28–30 October, 1981, Western Division, American Fisheries Society, Portland, OR, 62–73.

Buffington, J. M. and Montgomery, D. R. 1992. 'Effects of hydraulic roughness and sediment supply on bed surface textures in gravel-bed streams', *Abstract in EOS, Transactions, American Geophysical Union*, **73,** 231.

Carlson, J. Y., Andrus, C. W. and Froehlich, H. A. 1990. 'Woody debris, channel features, and macroinvertebrates of streams with logged and undisturbed riparian timber in northeastern Oregon, U.S.A.', *Canadian Journal of Fisheries and Aquatic Sciences*, **47,** 1103–1111.

Dietrich, W. E. and Whiting, P. 1989. 'Boundary shear stress and sediment transport in river meanders of sand and gravel', in Ikeda, S. and Parker, G. (Eds), *River Meandering*, American Geophysical Union, Washington, D.C., 1–50.

Dietrich, W. E., Kirchner, J. W., Ikeda, H. and Iseya, F. 1989. 'Sediment supply and the development of the coarse surface layer in gravel-bedded rivers', *Nature*, **340,** 215–217.

Dunteman, G. H. 1984. *Introduction to Multivariate Analysis*, SAGE Publications, Beverly Hills, CA.

Gehrels, G. E. and Berg, H. C. 1992. *Geologic Map of Southeast Alaska*, Miscellaneous Investigations Map I-1867, U.S. Geological Survey, Denver, CO.

Gehrels, G. E., McClelland, W. C., Samson, S. D., Patchett, P. J. and Jackson, J. L. 1990. 'Ancient continental margin assemblage in the northern Coast Mountains, southeast Alaska and northwest Canada', *Geology*, **18,** 208–211.

Goldfarb, R. J., Leach, D. L., Pickthorn, W. J. and Paterson, C. J. 1988. 'Origin of lode-gold deposits of the Juneau gold belt, southeastern Alaska', *Geology*, **16,** 440–443.

Harr, R. D., Levno, A. and Mersereau, R. 1982. 'Streamflow changes after logging 130-year-old Douglas fir in two small watersheds', *Water Resources Research*, **18,** 637–644.

Hogan, D. L. 1987. 'The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada', in Beschta, R. L., Blinn, T., Grant, G. E., Ice, G. G. and Swanson, F. J. (Eds), *Erosion and Sedimentation in the Pacific Rim*, Publication **165,** International Association of Hydrologic Sciences, Wallingford, 343–353.

Hogan, D. L. and Church, M. 1989. 'Hydraulic geometry in small, coastal streams: progress toward quantification of salmonid habitat', *Canadian Journal of Fisheries and Aquatic Sciences*, **46,** 844–852.

Hornbeck, J. W., Adams, M. B., Corbett, E. S., Verry, E. S. and Lynch, J. A. 1993. 'Long-term impacts of forest treatments on water yield: a summary for northeastern USA', *Journal of Hydrology*, **150,** 323–344.

Jones, S. H. and Fahl, C. B. 1994. *Magnitude and frequency of floods in Alaska and conterminous basins of Canada*, Water-Resources Investigations Report **93–4179,** U.S. Geological Survey, Anchorage, Alaska.

Keller, E. A. and Swanson, F. J. 1979. 'Effects of large organic material on channel form and fluvial process', *Earth Surface Processes*, **4,** 361–380.

Kinerson, D. 1990. *Bed Surface Response to Sediment Supply*, unpublished M.S. thesis, University of California, Berkeley, CA.

Klingeman, P. C. and Emmett, W. W. 1982. 'Gravel bedload transport processes', in Hey, R. D., Bathurst, J. C., and Thorne, C. R. (Eds), *Gravel-Bed Rivers*, John Wiley & Sons, Chichester, 141–179.

Leopold, L. B. and Maddock, T. Jr. 1953. *The hydraulic geometry of stream channels and some physiographic implications*, Professional Paper **252,** U.S. Geological Survey, Washington, D.C.

Lisle, T. E. 1981. 'The recovery of aggraded stream channels at gauging stations in northern California and southern Oregon', in Davies, R. H. and Pearce, A. J. (Eds), *Erosion and Sediment Transport in Pacific Rim Steeplands,* International Association of Hydrological Sciences, Publication No. **132,** 189–211.

Lisle, T. E. 1986a. 'Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California', *Geological Society of America Bulletin,* **97,** 999–1011.

Lisle, T. E. 1986b. 'Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska', *North American Journal of Fisheries Management,* **6,** 538–550.

Lisle, T. E. 1989. 'Sediment transport and resulting deposition in spawning gravels, north coastal California', *Water Resources Research* **25,** 1303–1319.

Lisle, T. E. and Hilton, S. 1992. 'The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams', *Water Resources Bulletin,* **28,** 371–383.

Lisle, T. E. and Madej, M. A. 1992. 'Spatial variation in armouring in a channel with high sediment supply', in, Billi, P., Hey, R. D., Thorne, C. R. and Tacconi, P. (Ed.), *Dynamics of Gravel-bed Rivers,* John Wiley & Sons, Chichester, 277–293.

Lyons, J. K. and Beschta, R. L. 1983. 'Land use, floods, and channel changes: upper Middle Fork Willamette River, Oregon (1936–1980)', *Water Resources Research,* **19,** 463–471.

Miller, M. C., McCave, I. N. and Komar, P. D. 1977. 'Threshold of sediment motion in unidirectional currents', *Sedimentology,* **24,** 507–528.

Montgomery, D. R. and Buffington, J. M. 1993. *Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition,* Report **TFW-SH10-93-002,** Timber/Fish/Wildlife Agreement, Washington State Department of Natural Resources, Olympia, WA.

Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M. and Pess, G. R. 1995. 'Pool spacing in forest channels', *Water Resources Research,* **31,** 1097–1105.

Nelson, J. M. and Smith, J. D. 1989a. 'Flow in meandering channels with natural topography', in Ikeda, S. and Parker, G. (Eds), *River Meandering,* American Geophysical Union, Washington, D.C., 69–102.

Nelson, J. M. and Smith, J. D. 1989b. 'Evolution and stability of erodible channel beds', in Ikeda, S. and Parker, G. (Eds), *River Meandering,* American Geophysical Union, Washington, D.C., 321–378.

Norusis, M. J. 1985. *SPSS-X Advanced Statistics Guide,* McGraw-Hill, New York.

Petit, F. 1994. 'Dimensionless critical shear stress evaluation from flume experiments using different gravel beds', *Earth Surface Processes and Landforms,* **19,** 565–576.

Reeves, G. H., Everest, F. H. and Sedell, J. R. 1993. 'Diversity of juvenile anadromous salmonid assemblages in coastal Oregon basins with different levels of timber harvest', *Transactions of the American Fisheries Society,* **122,** 309–317.

Reiser, D. W. and Bjornn, T. C. 1979. *Habitat Requirements of Anadromous Salmonids,* General Technical Report, **PNW-96,** U.S.D.A., Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Robison, E. G. and Beschta, R. L. 1990. 'Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, U.S.A.', *Earth Surface Processes and Landforms,* **15,** 149–156.

SAS Institute Inc. 1987. *SAS/STAT Guide for Personal Computers, Version 6 Edition,* SAS Institute Inc., Cary, NC.

Selkregg, L.L. 1974. *Alaska Regional Profiles, Southeast Region,* Arctic Environmental Information and Data Center, University of Alaska, Fairbanks, AK.

Smith, R. D. 1990. *Streamflow and Bedload Transport in an Obstruction-affected, Gravel-bed Stream,* Ph.D. Dissertation, Oregon State University, Corvallis.

Smith, R. D., Sidle, R. C. and Porter, P. E. 1993a. 'Effects on bedload transport of experimental removal of woody debris from a forest, gravel-bed stream', *Earth Surface Processes and Landforms,* **18,** 455–468.

Smith, R. D., Sidle, R. C., Porter, P. E. and Noel, J. R. 1993b. 'Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream', *Journal of Hydrology,* **152,** 153–178.

Sullivan, K. 1986. *Hydraulics and Fish Habitat in Relation to Channel Morphology,* Ph.D. thesis, Johns Hopkins University, Baltimore, MD.

Sullivan, K., Lisle, T. E., Dolloff, C. A., Grant, G. E. and Reid, L. M. 1987. 'Stream channels: the link between forests and fishes', in Salo, E.O. and Cundy, T.W. (Eds), *Streamside Management: Forestry and Fishery Interactions,* Contribution No. 57, College of Forest Resources, Institute of Forest Resources, University of Washington, Seattle, WA, 39–97.

Swanson, F. J., Lienkaemper, G. W. and Sedell, J. R. 1976. *History, Physical Effects, and Management Implications of Large Organic Debris in Western Oregon Streams,* General Technical Report, **PNW-56,** U.S.D.A., Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Vanoni, V. A. (Ed.) 1975. *Sedimentation Engineering,* Manuals and Reports on Engineering Practice no. **54,** American Society of Civil Engineers, New York.

Whiting, P. J. and Bradley, J. B. 1993. 'A process-based classification system for headwater streams', *Earth Surface Processes and Landforms,* **18,** 603–612.

Wolman, M. G. 1954. 'A method of sampling coarse river-bed material', *Transactions, American Geophysical Union,* **35,** 951–956.

Zimmerman, R. C., Goodlet, J. C. and Comer, G. H. 1967. *The Influence of Vegetation on Channel Form of Small Streams,* Publication **75,** International Association of Scientific Hydrology, 255–275.